Jet substructure in Heavy Ion Collisions

Sensitivity to medium-induced radiation and color decoherence

Yacine Mehtar-Tani
INT, University of Washington

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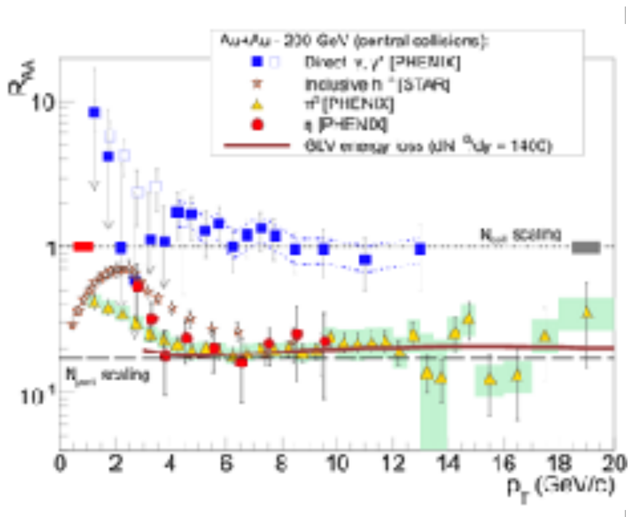
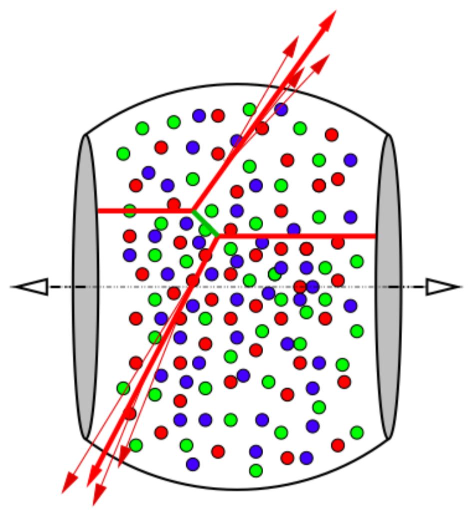
@ BNL

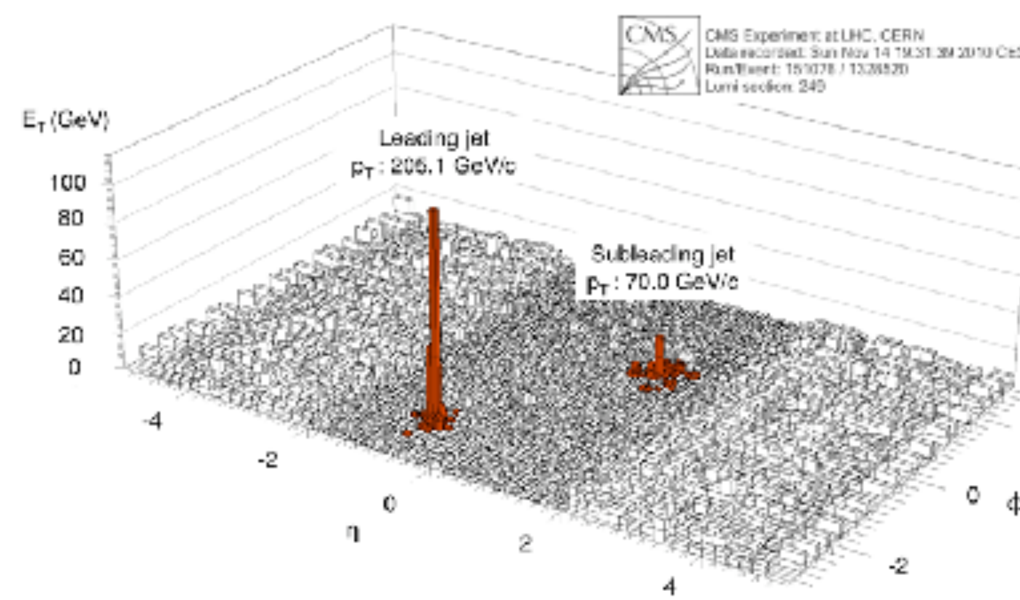
Probing the quark-gluon-plasma with jets

from

inclusive Jet observables





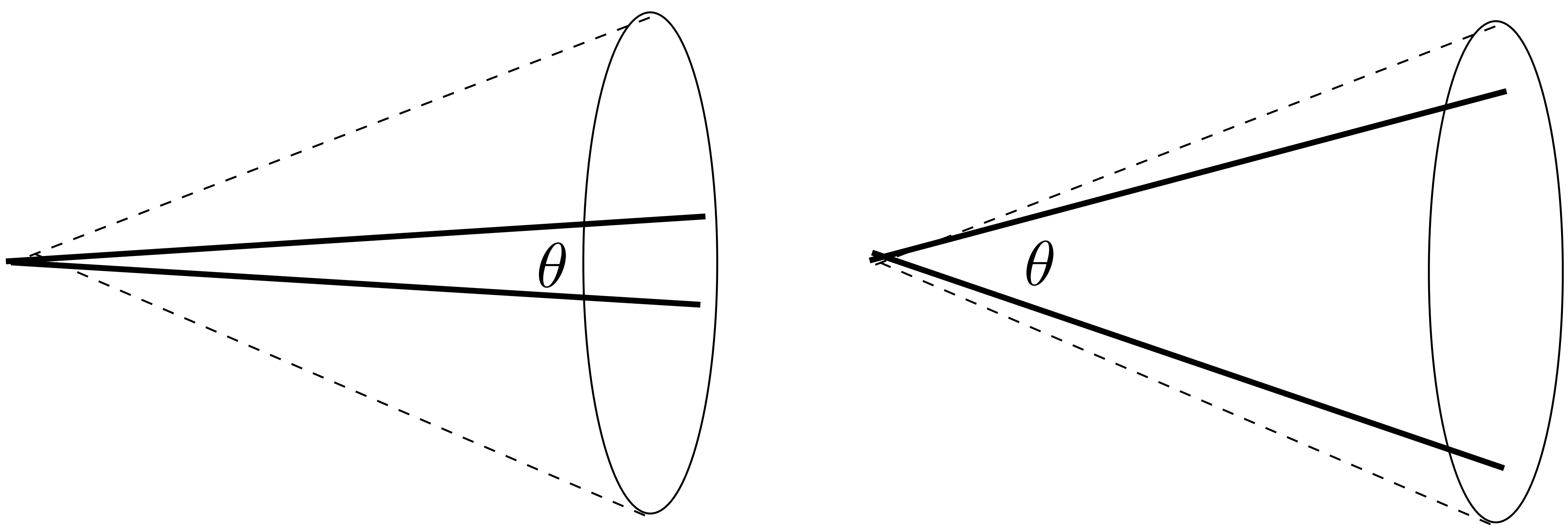


to Jet (sub)structure

(angular distribution, fragmentation functions, jet shapes, etc)

 MT, Tywoniuk, arXiv:1610.08930

- Use jet substructure techniques to investigate the transition from color coherence to decoherence by varying the angle between subjets:

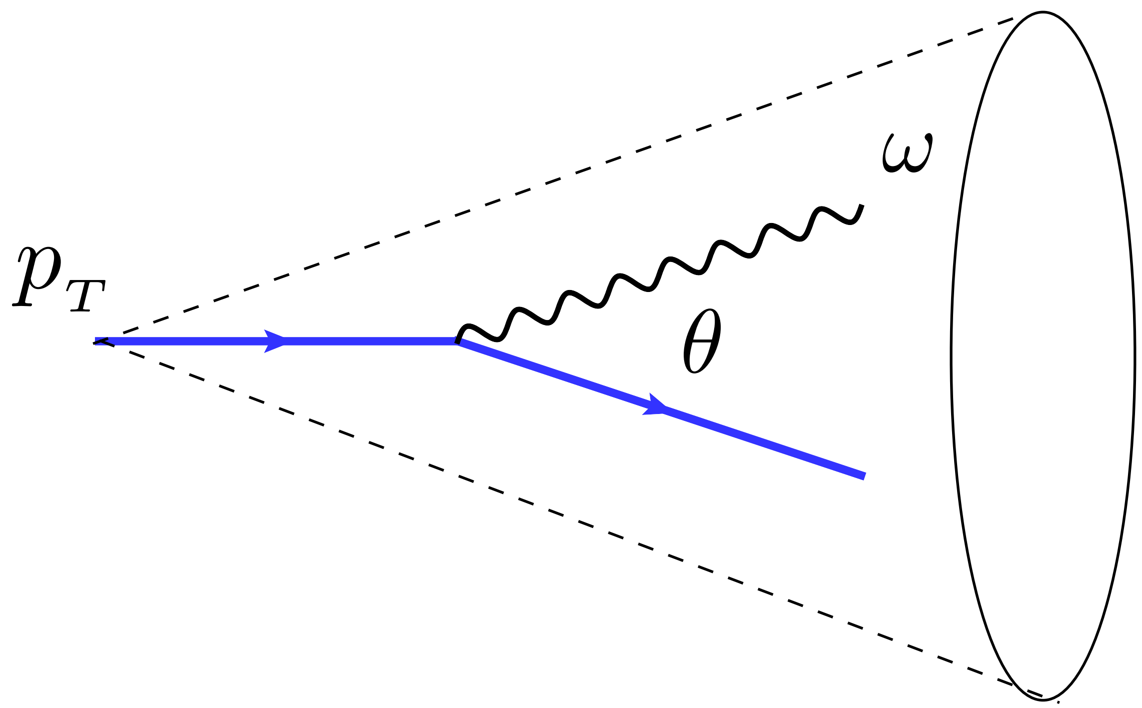


Energy loss dependence on the angular separation?

Jets from pQCD

Jets in pQCD

- Building block probability for parton cascades in vacuum



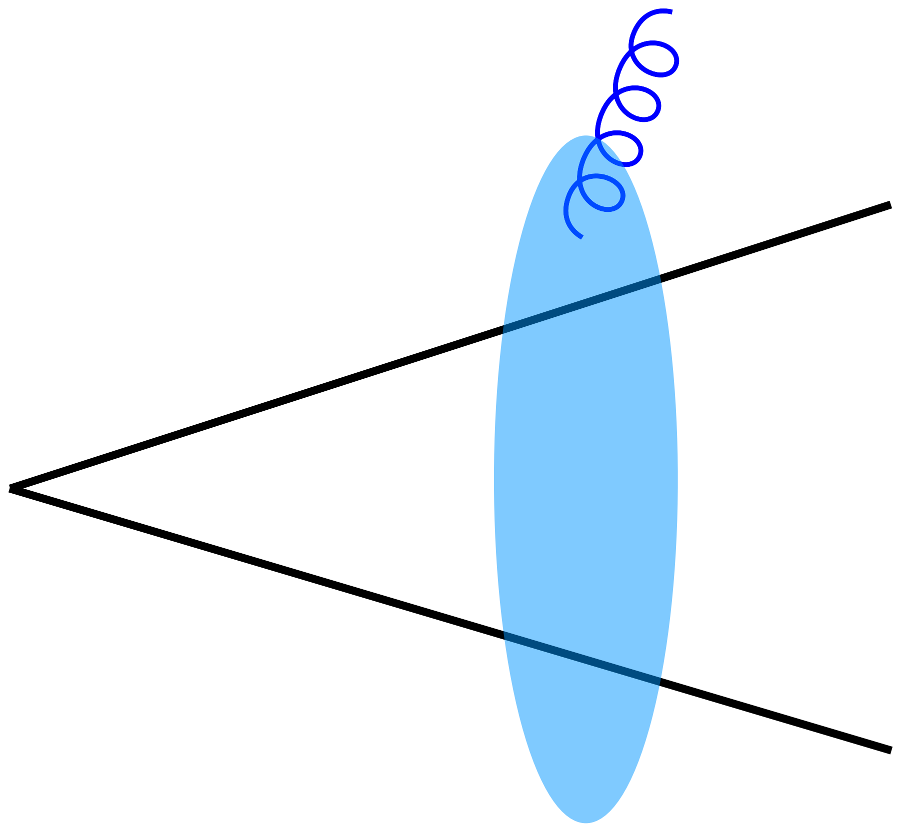
$$\mathrm{d}P \sim \alpha_s C_R \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}\omega}{\omega}$$

$\Longrightarrow$ collimation of jets

Large phase space for multiple branching: many particles Produced (Implemented in Event generators such as PYTHIA, HERWIG, SHERPA, etc.)

Jets in pQCD

- Building block probability for parton cascades in vacuum



large angle radiation is suppressed
(sensitive to total color charge)

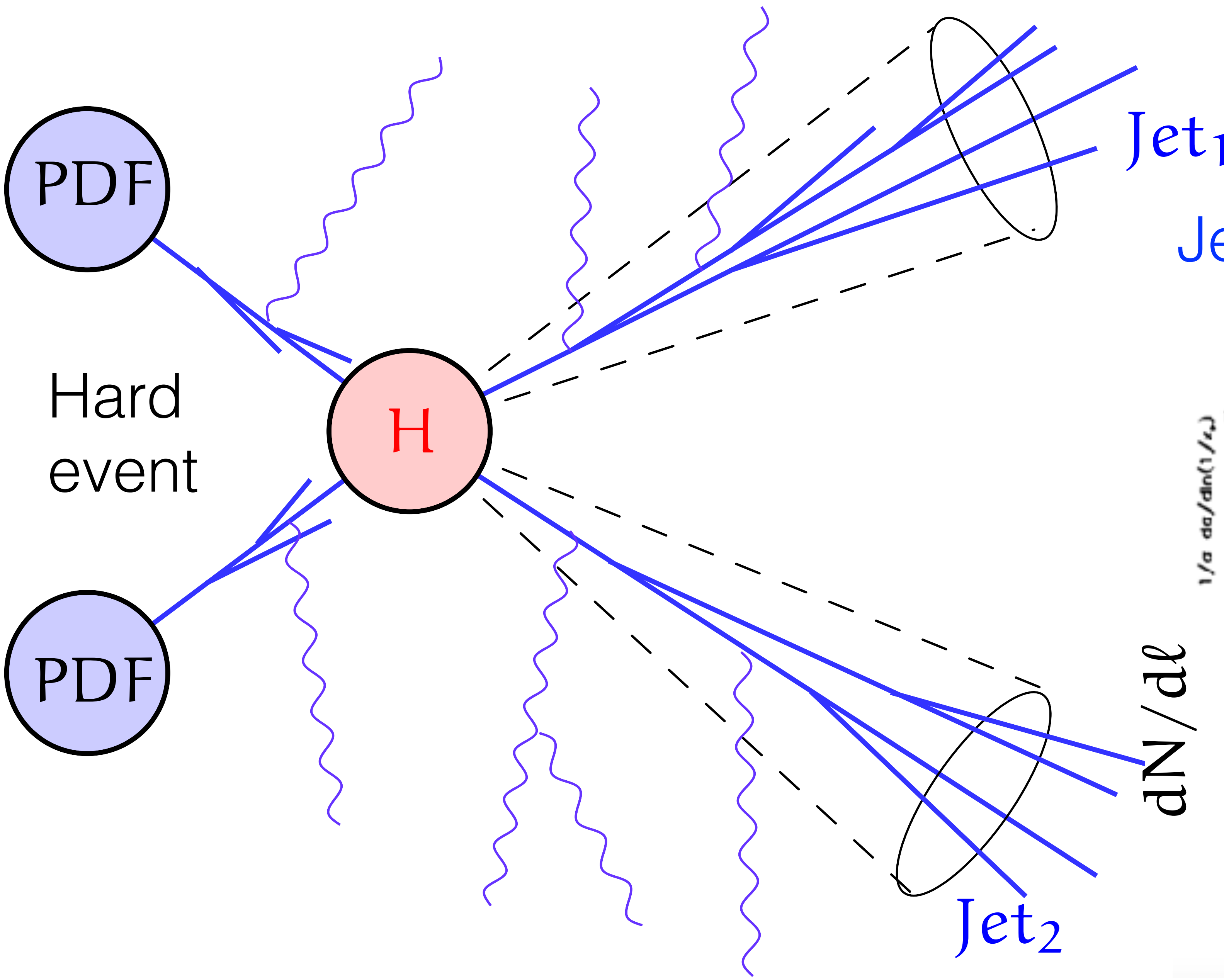
- Radiation pattern for a color singlet Antenna :

$$\mathrm{d}P \sim \alpha_s C_R \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}\omega}{\omega} \Theta(\theta_0 - \theta)$$

Jet in pQCD (color coherence)

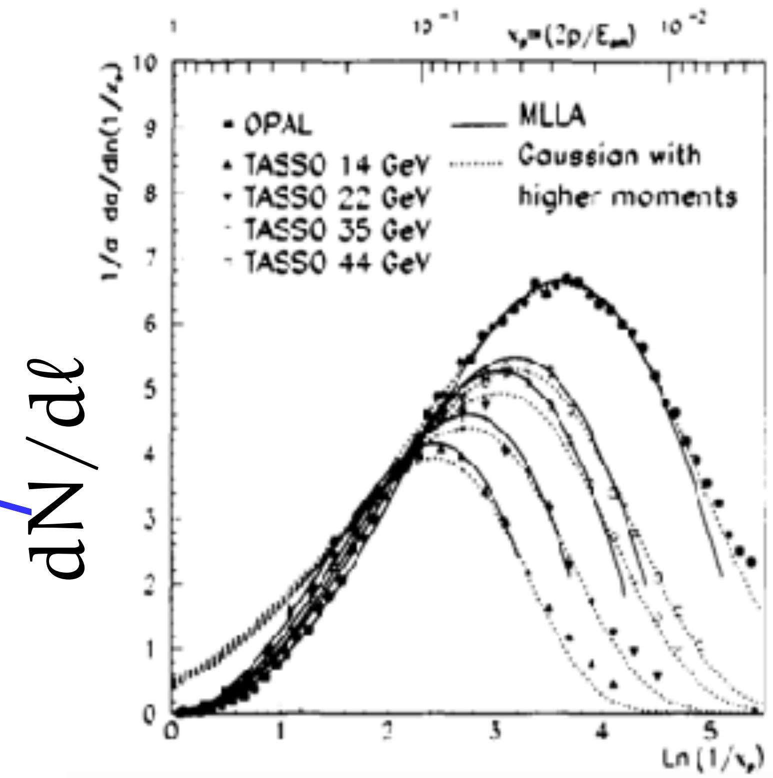
coherent soft radiation

[Bassetto, Ciafaloni, Marchesini, Mueller, Dokshitzer, Khoze, Toyan, Collins, Soper, Sterman … 1980's]



Jet function (universal)

collinear splittings



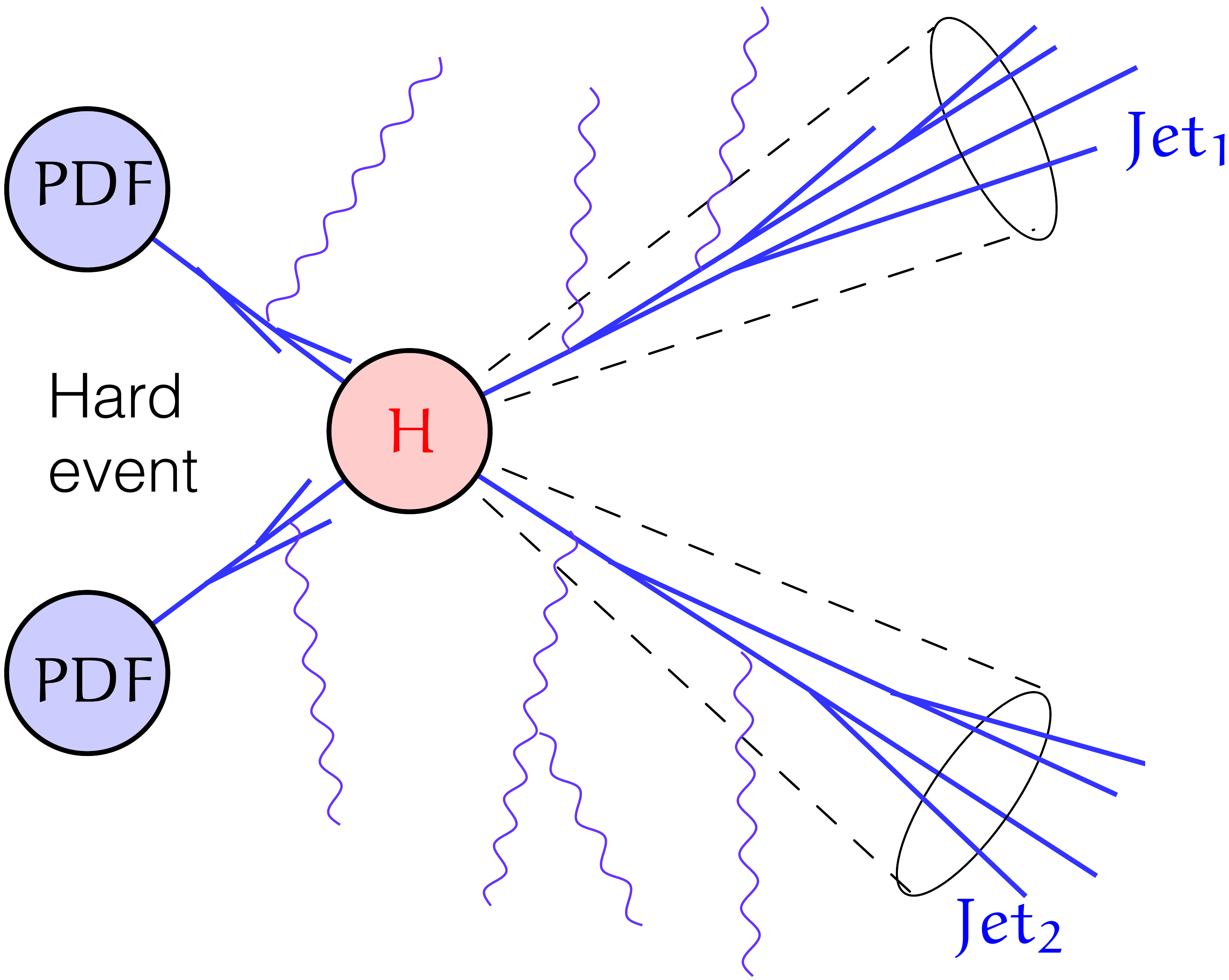
$$\ell = \ln \frac{1}{z}$$

Factorization of the cross-section

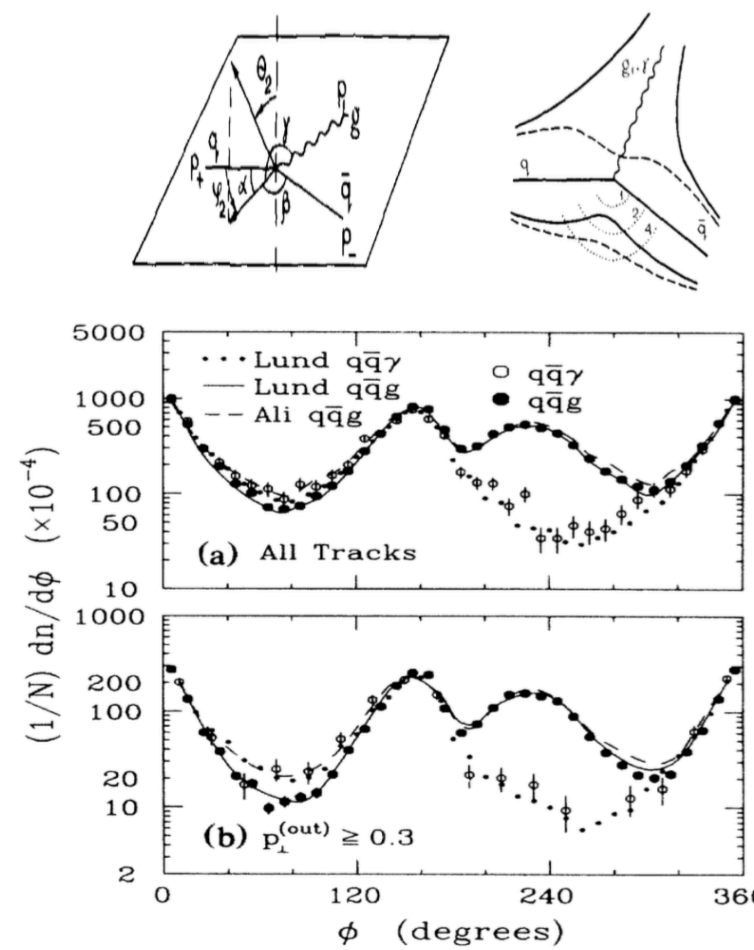
$$\sigma \sim \mathrm{PDF} \times H \times J_1 \times J_2 \times S$$

Jet in pQCD (color coherence)

coherent soft radiation



Interjet hadronic activity: "Stringy" fragmentation from pQCD



Factorization of the cross-section

$$\sigma \sim \mathrm{PDF} \times H \times J_1 \times J_2 \times S$$

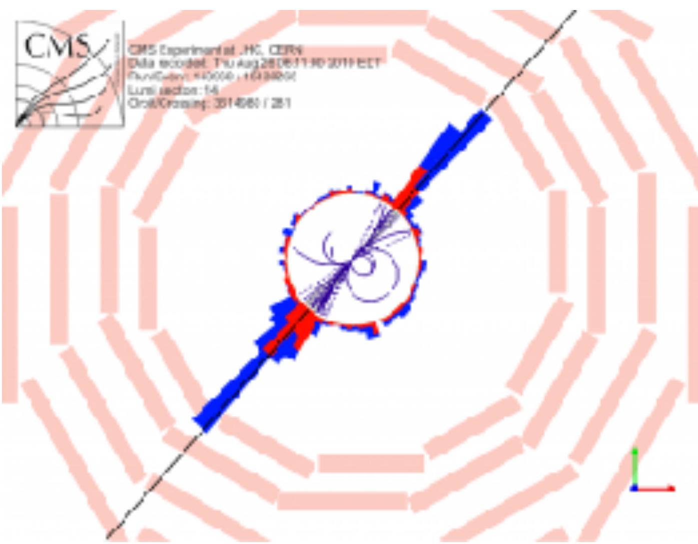
Jet observables of two types

- Infrared-Collinear (IRC) safe observables: sum over final state hadrons $\longrightarrow$ cancellations of divergences. Ex: event shape: thrust, jet mass, jet spectra, etc. Resummation of large logs, e.g. log R can be necessary

- Collinear sensitive observables: pQCD still predictive (factorization theorems). Ex: Fragmentation Functions

Jets in pQCD
(high precision)

Parton Energy loss



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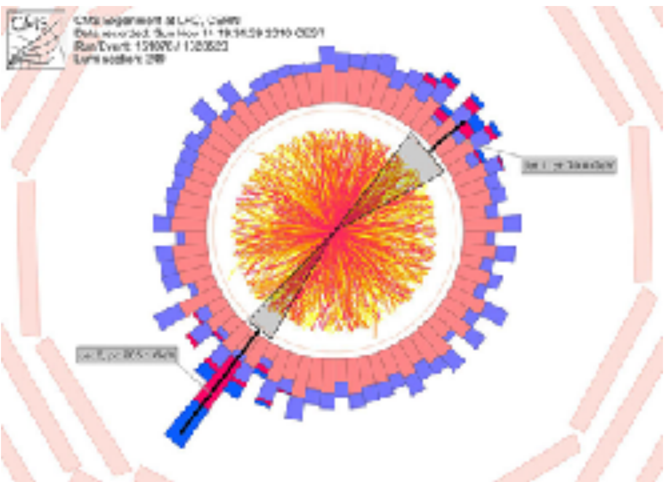


Theory of jets in the plasma

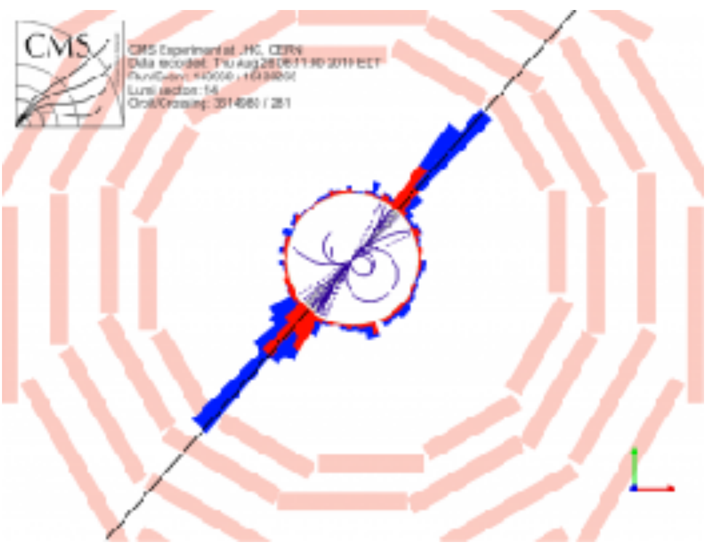
(i) Parton cascade of two kinds
(vacuum and medium induced)

(ii) Color decoherence

Jets in pQCD

(high precision)

Parton Energy loss



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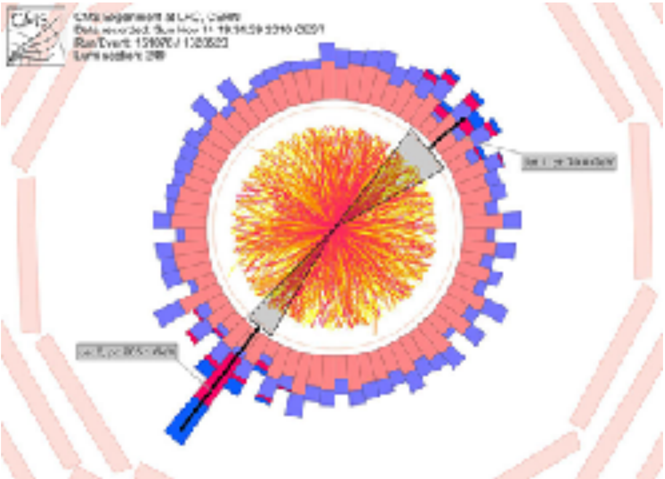


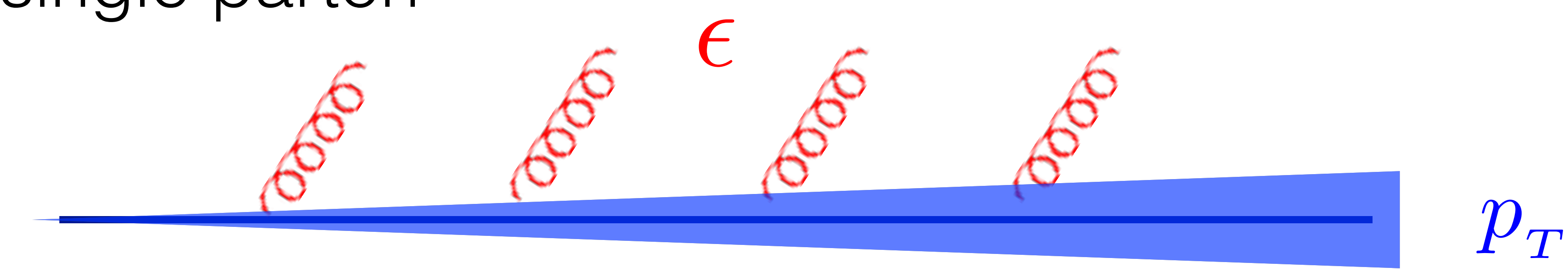
Theory of jets in the plasma

$\Rightarrow$ Also important for the problem of

thermalization in HIC

Jet quenching and fluctuations

- Standard energy loss picture: medium-induced radiation off a single parton



- Energy loss probability for large media

$$D(\epsilon) \equiv \frac{\sqrt{\omega_{\rm br}}}{\epsilon^{3/2}}\, \mathrm{e}^{-\frac{\pi\omega_{\rm br}}{\epsilon}} \qquad \omega_{\rm br} \equiv \bar{\alpha}^2\, \hat{q}\, L^2$$

[Baier, Dokshitzer, Mueller, Schiff, JHEP (2001) Jeon, Moore (2003)]

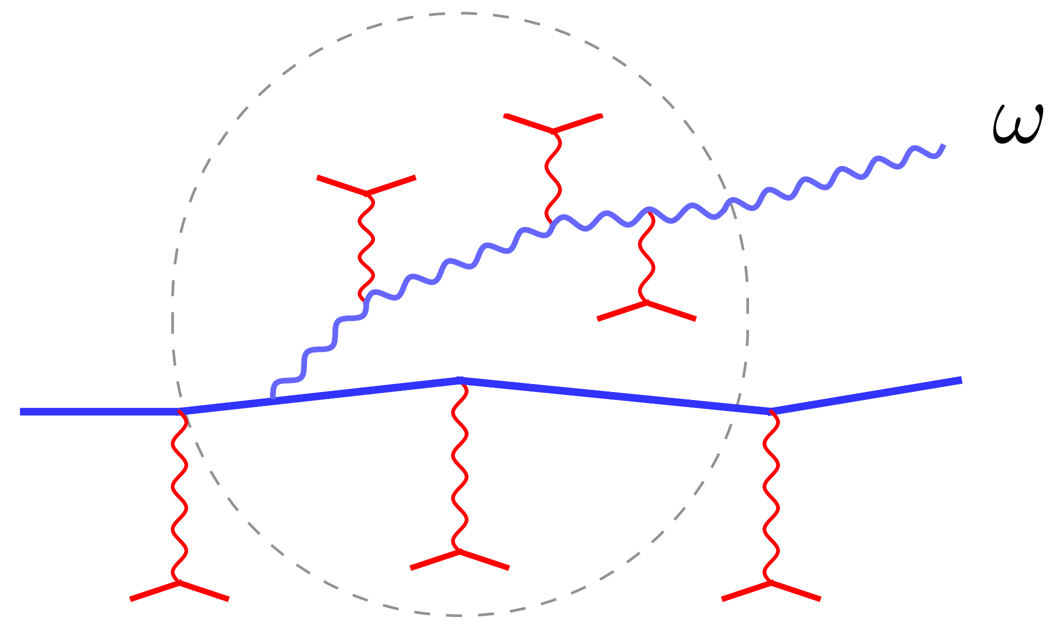
- Single scale: large fluctuations of energy loss
- Medium properties encoded in the jet quenching parameter

$$\hat{q} \sim \frac{\langle k_\perp^2 \rangle}{L}$$

Longitudinal coherence (LPM effect)

- Radiation triggered by multiple scatterings

- Landau-Pomeranchuk-Migdal suppression (coherent radiation)



$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \alpha_s C_R \sqrt{\frac{\omega_c}{\omega}}$$

$$t_f = \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

formation time

- Maximum suppression when $t_f \gtrsim L \Rightarrow \omega > \omega_c = \hat{q} L^2$

- Minimum radiation angle $\theta > \theta_c \equiv 1/\sqrt{\hat{q} L^3}$

[Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996)]

[Wiedemann (2001) Arnold, Moore,Yaffe (2002)]

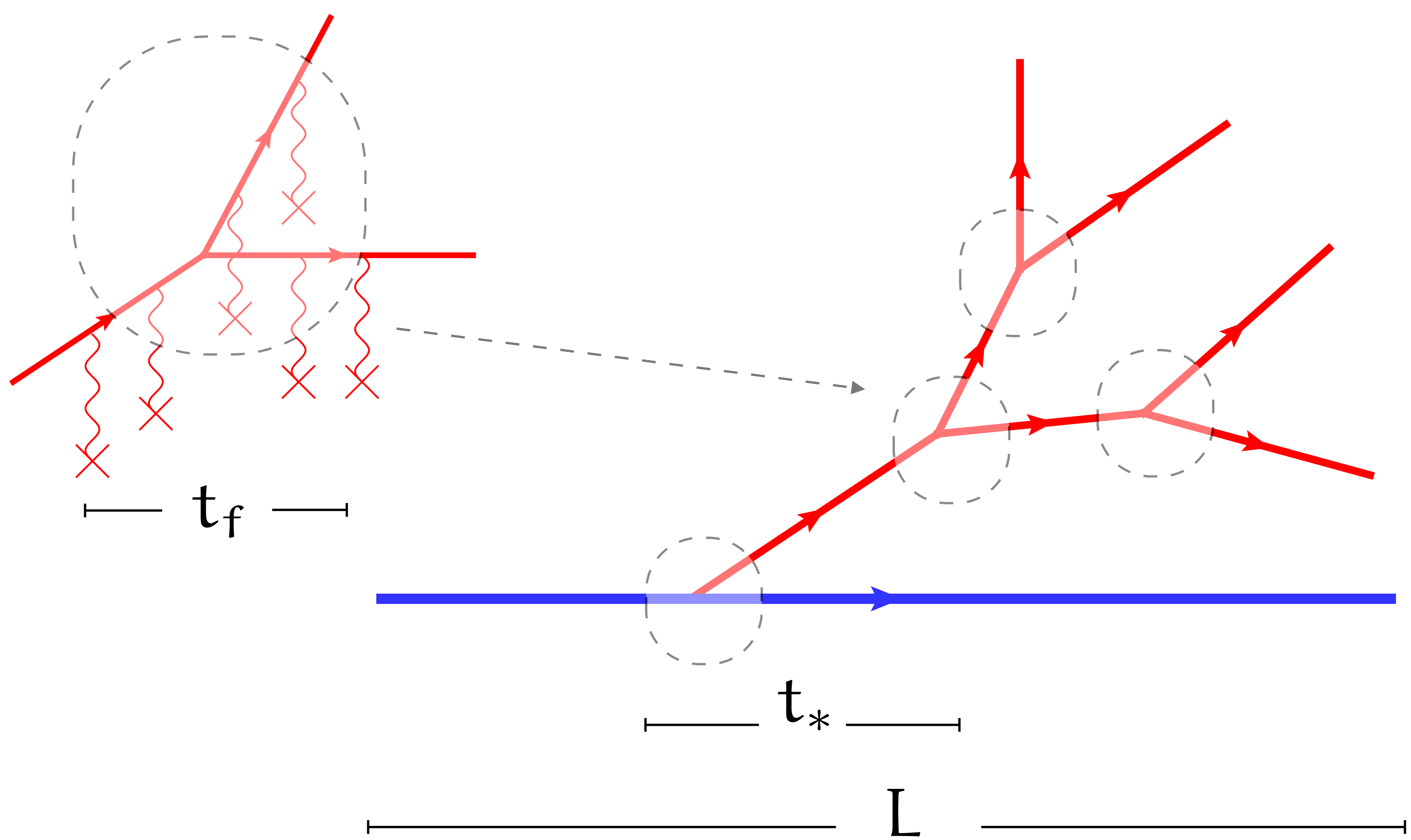
Probabilistic picture of in-medium cascade

- Multiple (independent) branchings regime:

$$t_f \ll t_{\rm br} \ll L$$

- Incoherent branchings: randomization of color due to rescatterings

[Blaizot, Dominguez, Iancu, MT (2013-2014)]



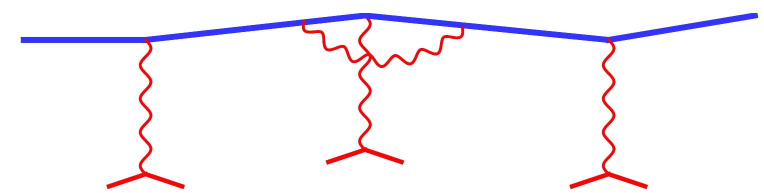
branching time

$$t_{\rm br}(\omega) \sim \frac{1}{\alpha_s} t_f(\omega)$$

Renormalization of the jet quenching parameter

- Radiative corrections to pt-broadening to DLA accuracy

$$\langle k_\perp^2 \rangle \simeq \hat{q} L \left(1 + \frac{\alpha_s N_c}{2\pi} \ln^2 \frac{L}{\tau_0} \right)$$



[Wu (2011) Liou, Mueller, Wu (2014) Blaizot, Iancu, Dominguez, MT (2014)]

- The double log can be absorbed in a redefinition of $\hat{q}$

$$\hat{q} \equiv \hat{q}_0 \left(1 + \frac{\alpha_s N_c}{2\pi} \ln^2 \frac{L}{\tau_0} \right)$$

[Blaizot, MT (2014)]

Eloss anomalous scaling: $\Delta E \sim L^{2+\gamma}$ with $\gamma \equiv \sqrt{\frac{4\,\alpha_s N_c}{\pi}}$

Between the plain pQCD L^2 and AdS/CFT results L^3

[Gubser et al, Hatta et al, Chesler et Yaffe (2008)]

Energy flow at large angle

[Blaizot, Iancu, Fister, Torres, MT (2013-2014) Kurkela, Wiedemann (2014)]

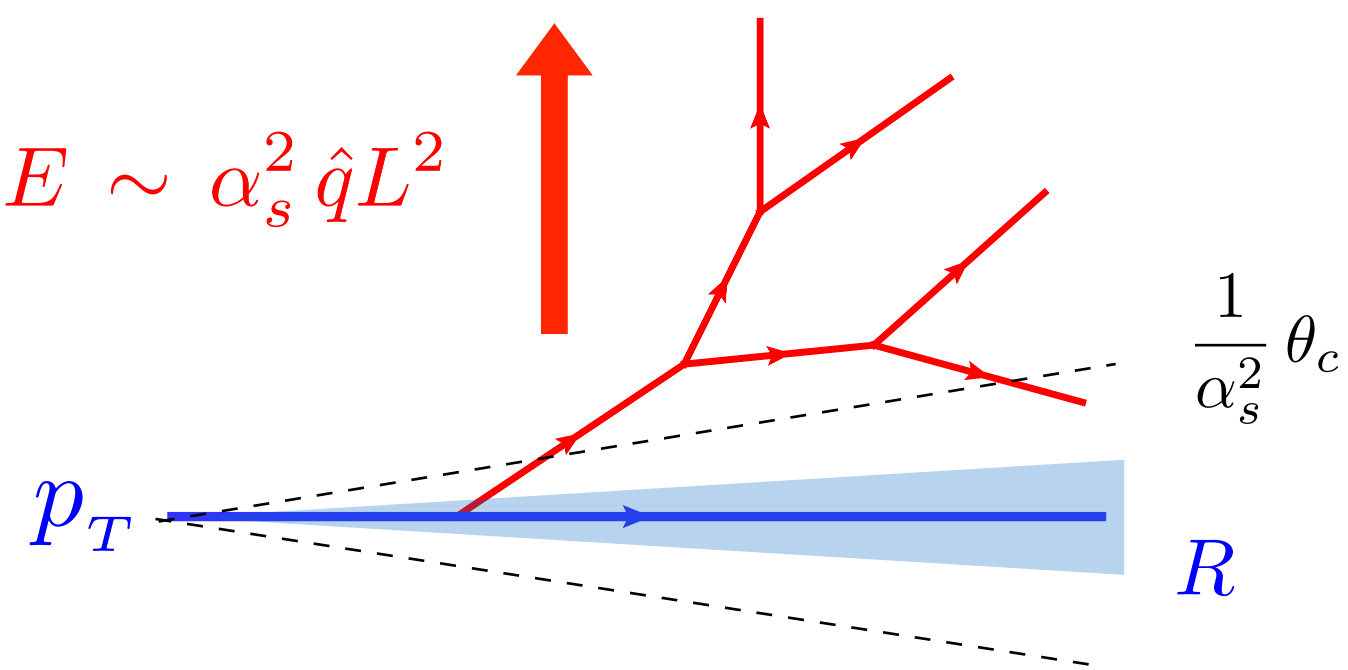
- Multiple branchings at parametrically large angle

$$\theta_{\rm br} \gg \frac{1}{\alpha_s^2}\theta_c \gg R$$

- Constant energy flow from jet energy scale p_T energy down to the medium temperature scale $\omega \sim T$

Energy lost to the medium:

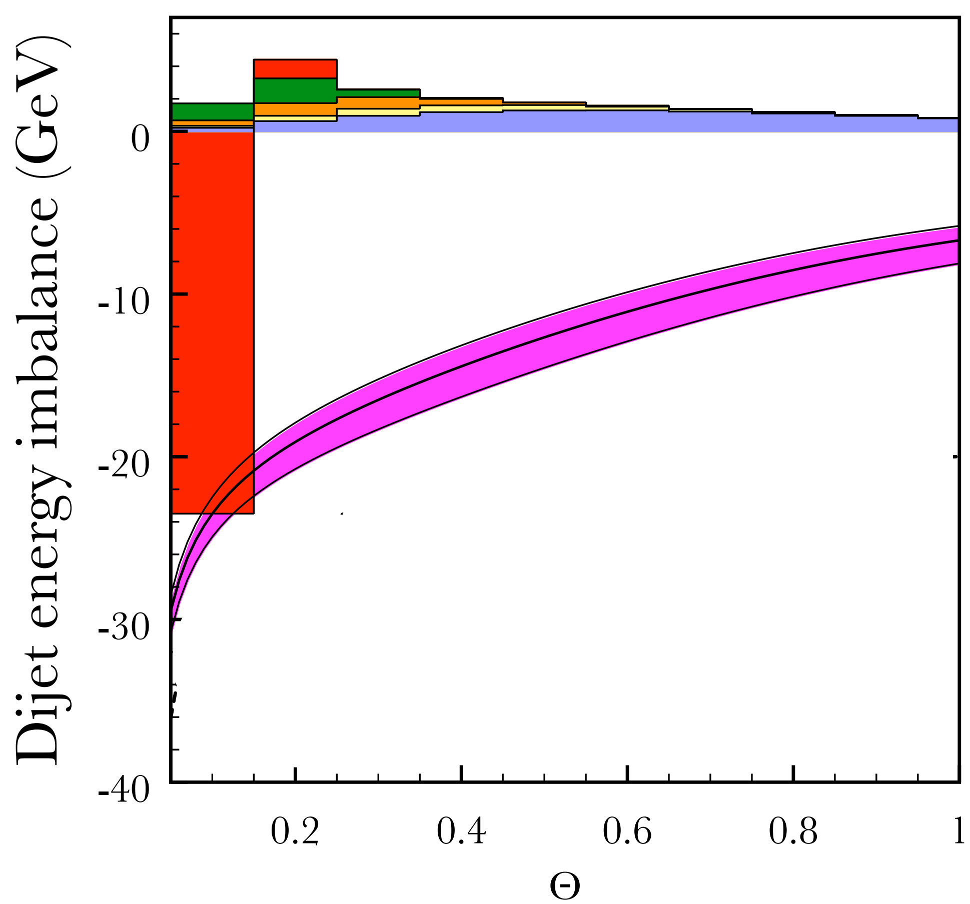
$$\Delta E \sim \alpha_s^2\, \hat{q} L^2$$



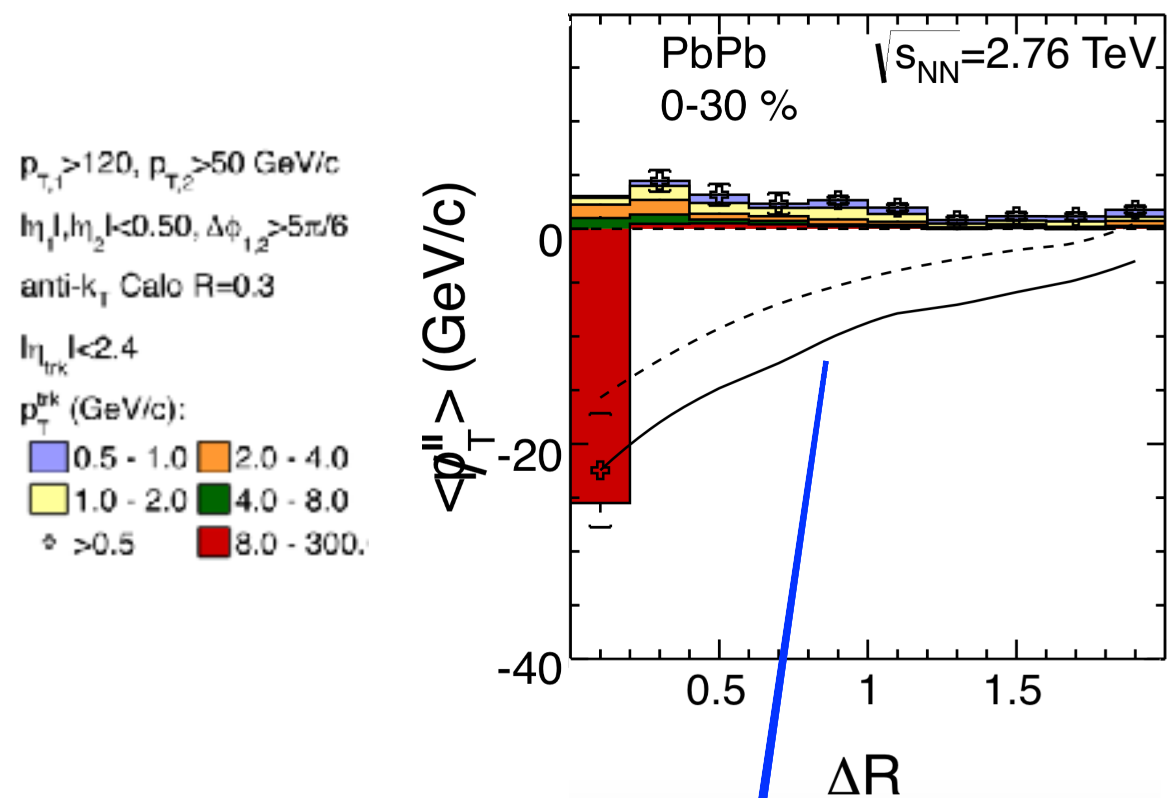
Recovering the missing jet energy

Turbulent transport of energy to large angles

[Blaizot, MT, Torres PRL (2014)]



Might explain missing p_T in dijet events (CMS 2011-2014)

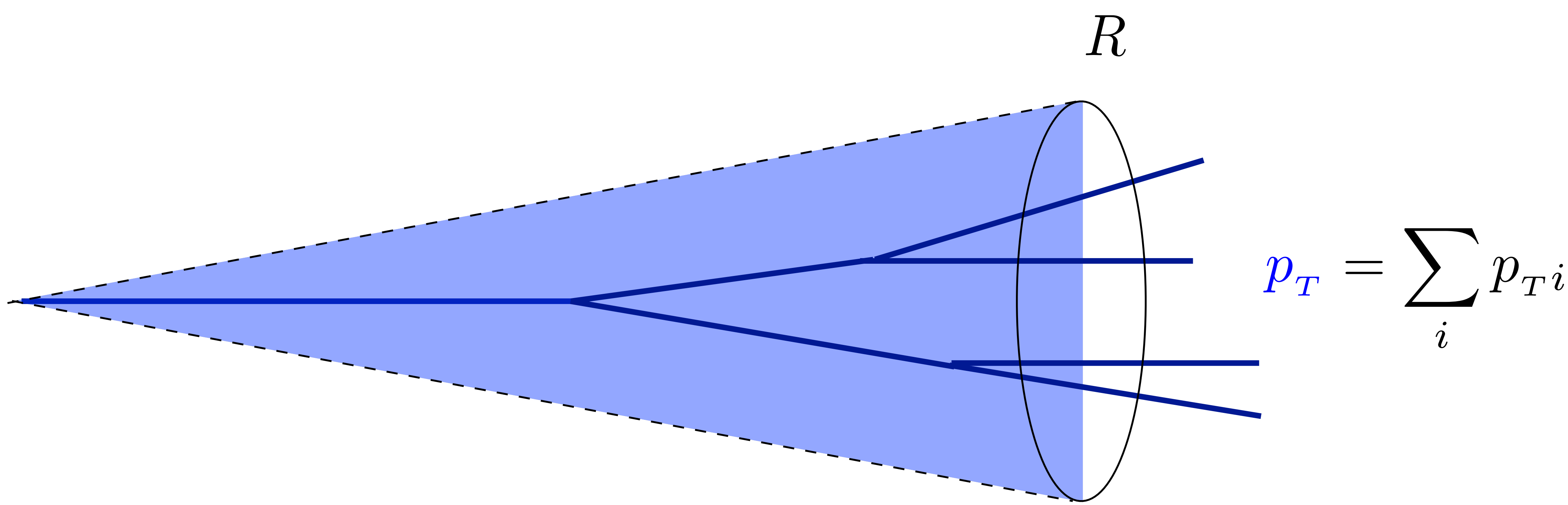


The energy lost is recovered at very large angle

How does energy loss
depend on jet substructure?

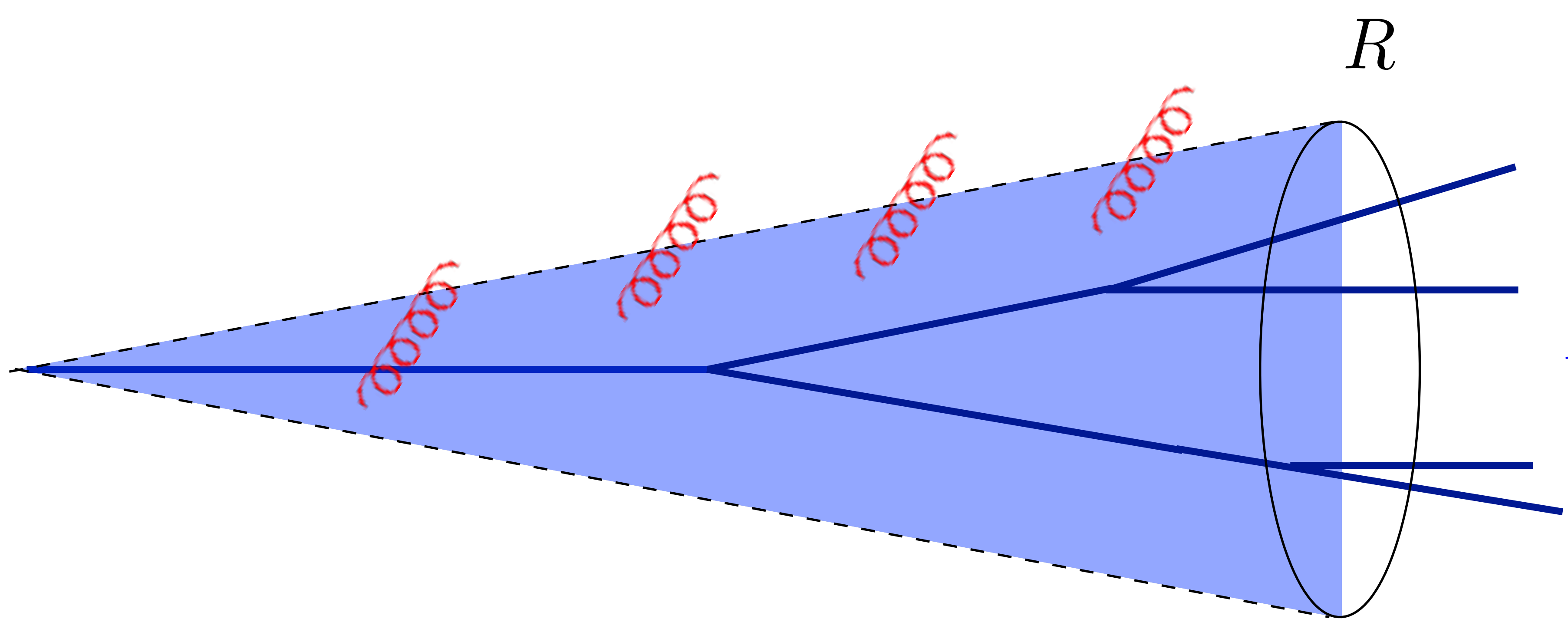
Jet quenching and fluctuations

- Jets are muti-parton systems
- Not uniquely defined. Depend on inputs such as the cone size R, reconstruction algorithms (C/A, kt, anti-kt, etc) …



Jet quenching and fluctuations

- Jet energy loss depend on the number of resolved color charges
- Need to account for fluctuations of energy loss due to fluctuation in the jet substructure



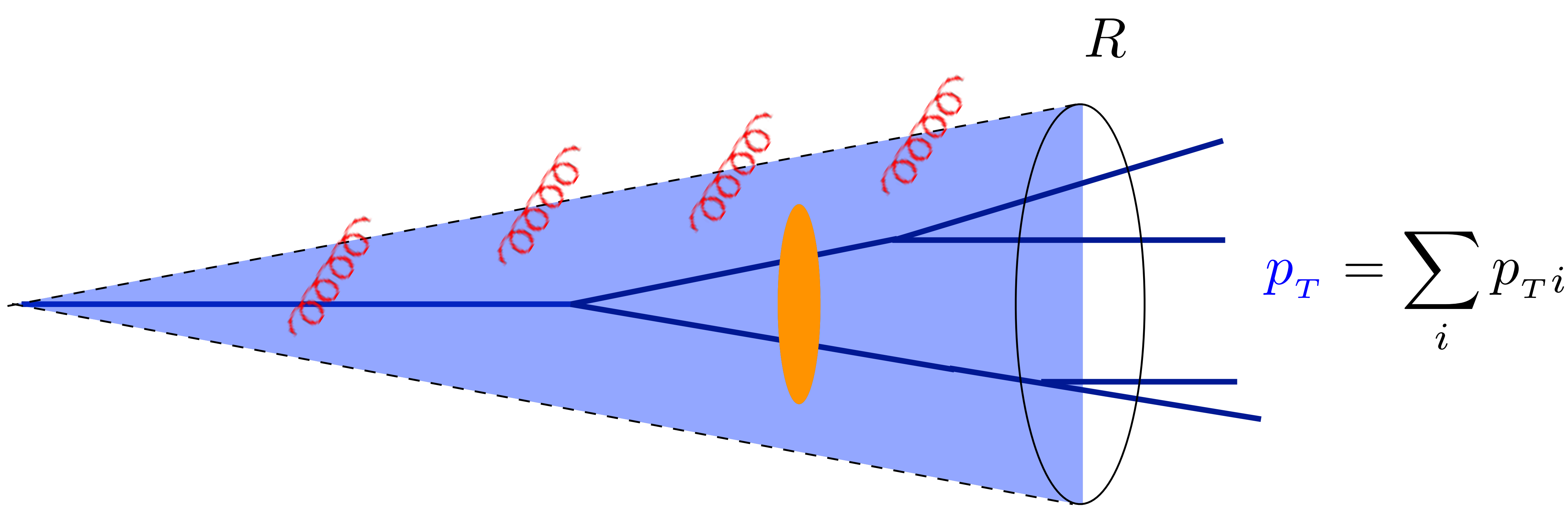
$$p_T = \sum_i p_{Ti}$$

Jet quenching and fluctuations

Two limiting scenarios for jet energy loss

(i) coherent Eloss, as a single color charge (parton)

(ii) incoherently as multiple charges



Jet quenching and fluctuations

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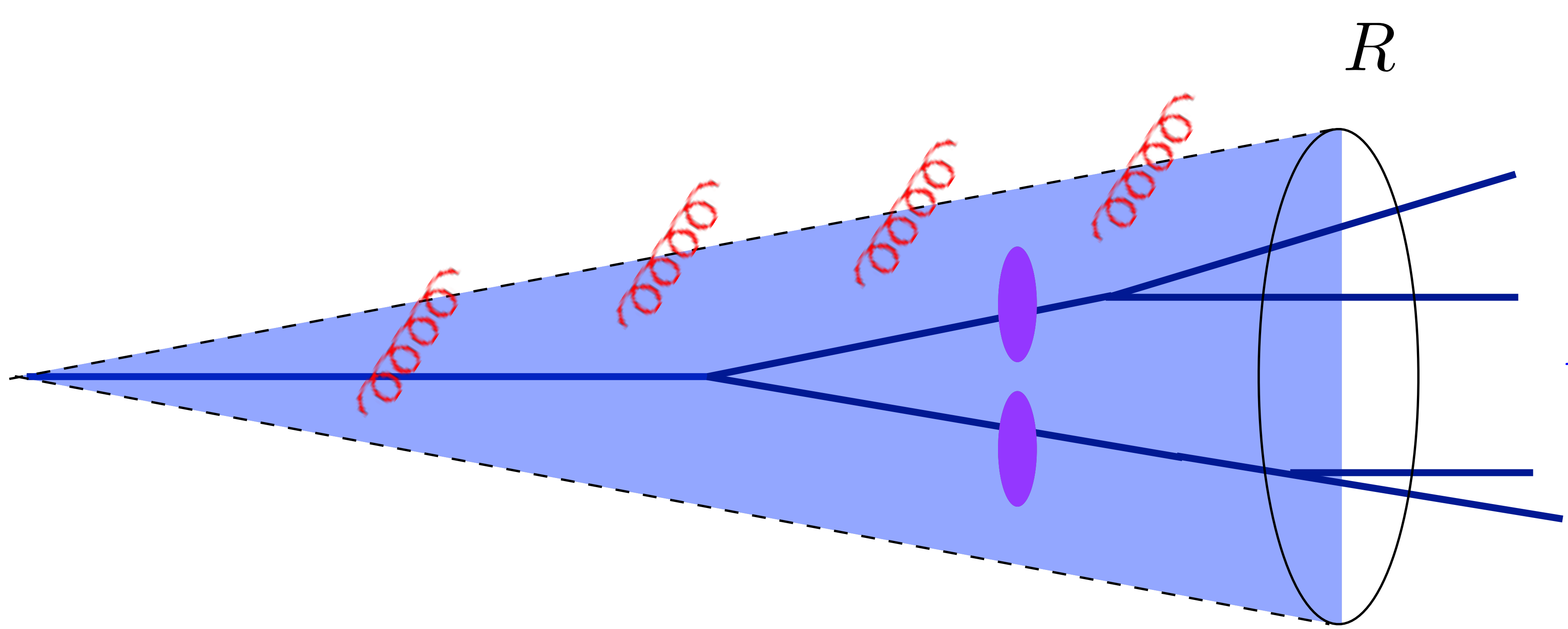
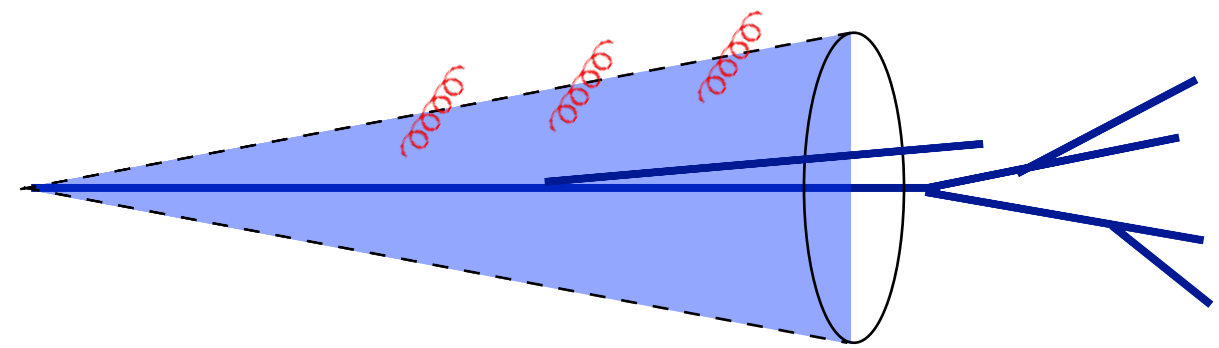


$$p_T = \sum_i p_{T\,i}$$

Coherent limit of QCD

- A large fraction of parton splittings are collinear or soft and hence occur outside the medium

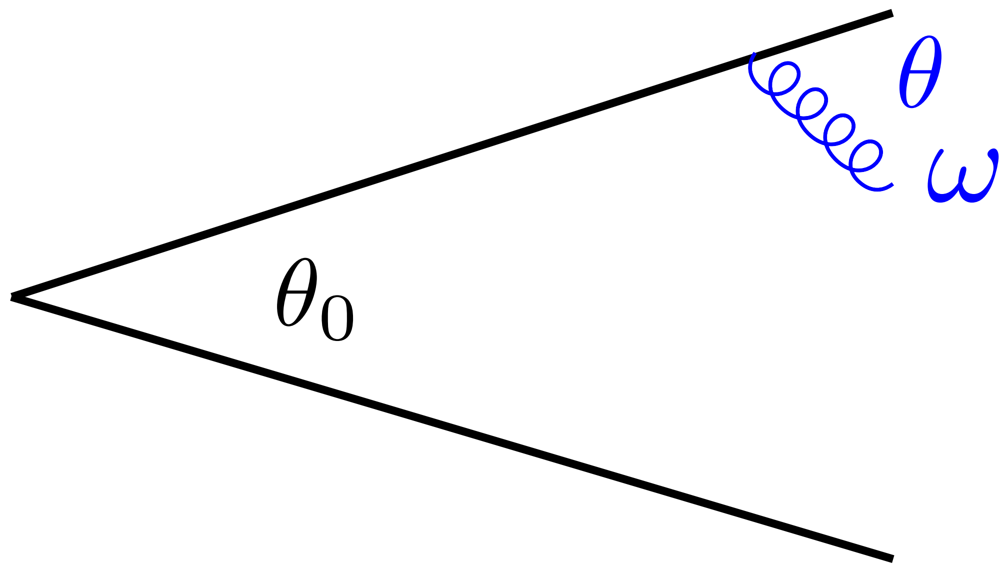
$$t_{\text{form}} = \frac{1}{\omega\theta^2} > L$$



- Some parton split inside the medium at small enough angle so that the medium on average does not resolve the two individual charges
- Hence, single parton energy loss approximation applies when the jet cone size R is small enough (but compared to what? what are the relevant scales?)

Color decoherence: the antenna setup

- The radiation spectrum of a color singlet antenna reads



Suppression of large angle radiation due to color coherence

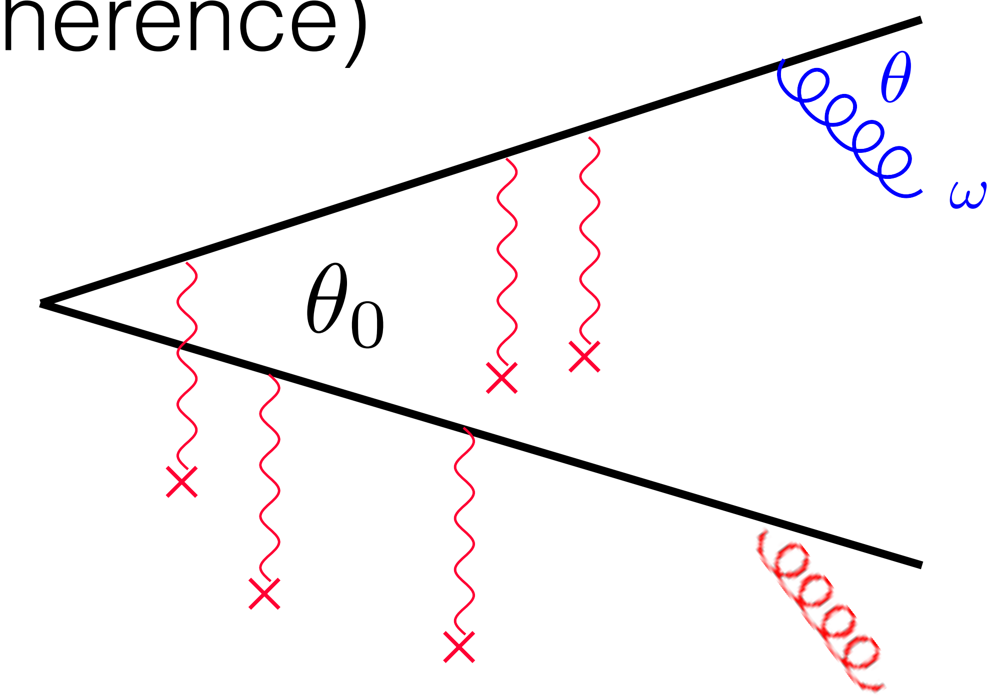
$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}\theta} = \frac{\alpha_s\, C_R}{\pi\, \theta} \Theta(\theta_0 - \theta)$$

- Building block for QCD jet evolution (corrects virtuality evolution with angular ordering)

Color decoherence: the antenna setup

- The presence of a colored medium causes rapid color randomization of the pair altering the radiation pattern (decoherence)

MT, Salgado, Tywoniuk PRL (2011), PLB (2012), JHEP (2011-2012)
Casalderrey-Solana, Iancu JHEP (2012)
Casalderrey-Solana, MT, Salgado, Tywoniuk PLB (2013)



more radiation off individual charges at large angle when

$$\theta_0 > \theta_c$$

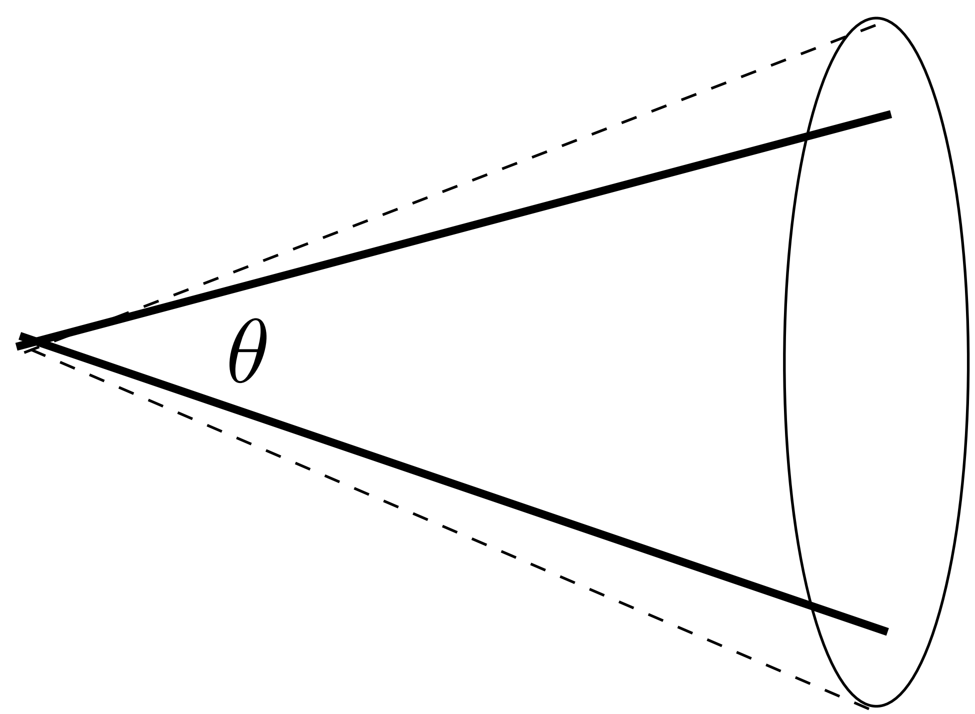
$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}\theta} = \frac{\alpha_s C_R}{\pi \theta} \left[\Theta(\theta_0 - \theta) + \Delta_{\mathrm{med}} \Theta(\theta - \theta_0) \right]$$

$$\Delta_{\mathrm{med}} = = 1 - \mathrm{e}^{-\frac{1}{12}(\theta_0/\theta_c)^2} \quad \begin{cases} 1 & \theta_0 \gg \theta_c \equiv 1/\sqrt{\hat{q}L^3} \\ 0 & \theta_0 \ll \theta_c \end{cases}$$

decoherence parameter

Probing color decoherence

Investigate energy loss of a subset of jets characterized by an early hard and relatively wide angle splitting (short formation time)

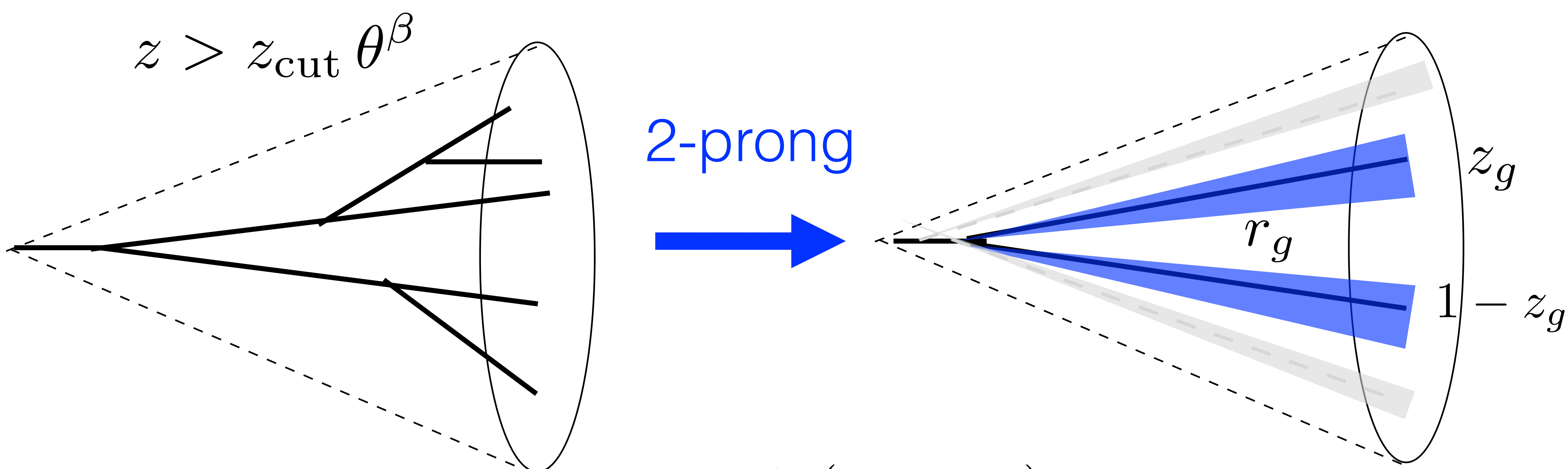


Jet grooming techniques (SoftDrop)

- Use SoftDrop de-clustering grooming technique developed to reduce the soft contamination from PileUp and UE in order to identify events with boosted W, Z, Higgs, etc)

Identify the first splitting that passes the cut

Dasgupta, Fregoso, Marzani, Salam JHEP (2013)
Larkoski, Marzani, Soyez, Thaler JHEP (2014)
Larkoski, Marzani, Thaler PRD (2015)



$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

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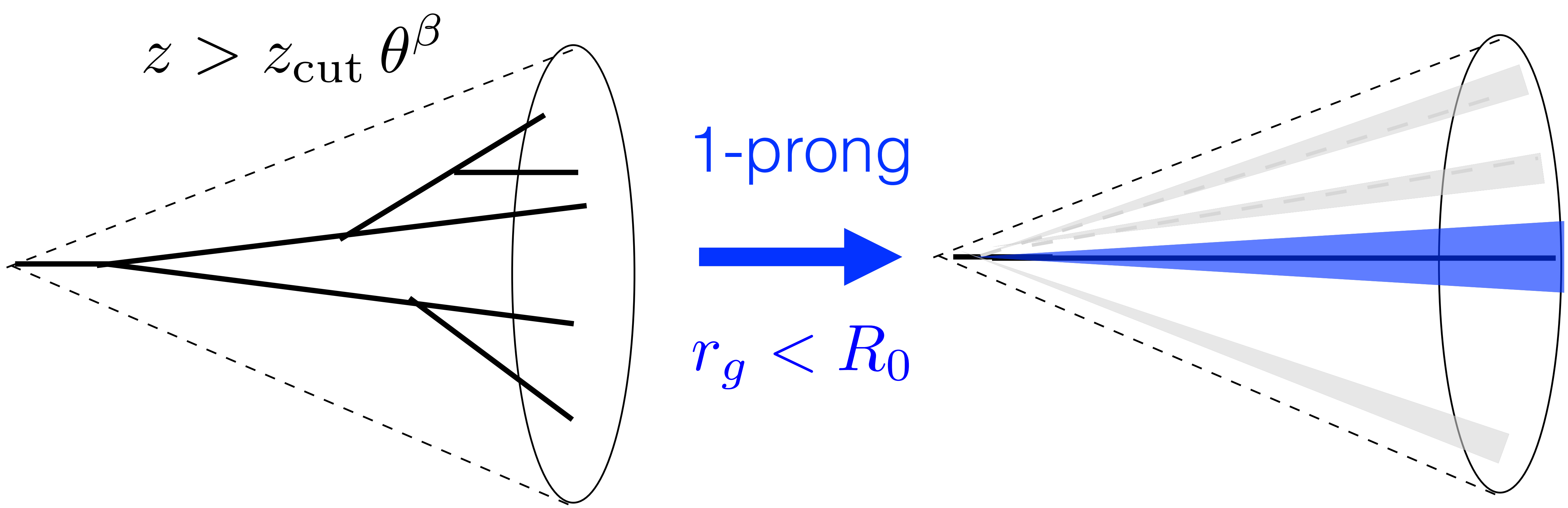


Experimental angular resolution scale (R_0=0.1 CMS): a fraction of jets is made of one-pronged

Jet grooming techniques (SoftDrop)

- In the Modified Leading Log Approximation

$$p(z_g) = \underbrace{\bar{\alpha} \int_0^R \frac{\mathrm{d}\theta}{\theta} \Delta(R,\theta)\, P(z_g)}_{\text{2 -prong probability}} + \underbrace{\Delta(R,R_0)\, \delta(1-z_g)}_{\text{1 -prong probability}}$$

- Sudakov form factor:

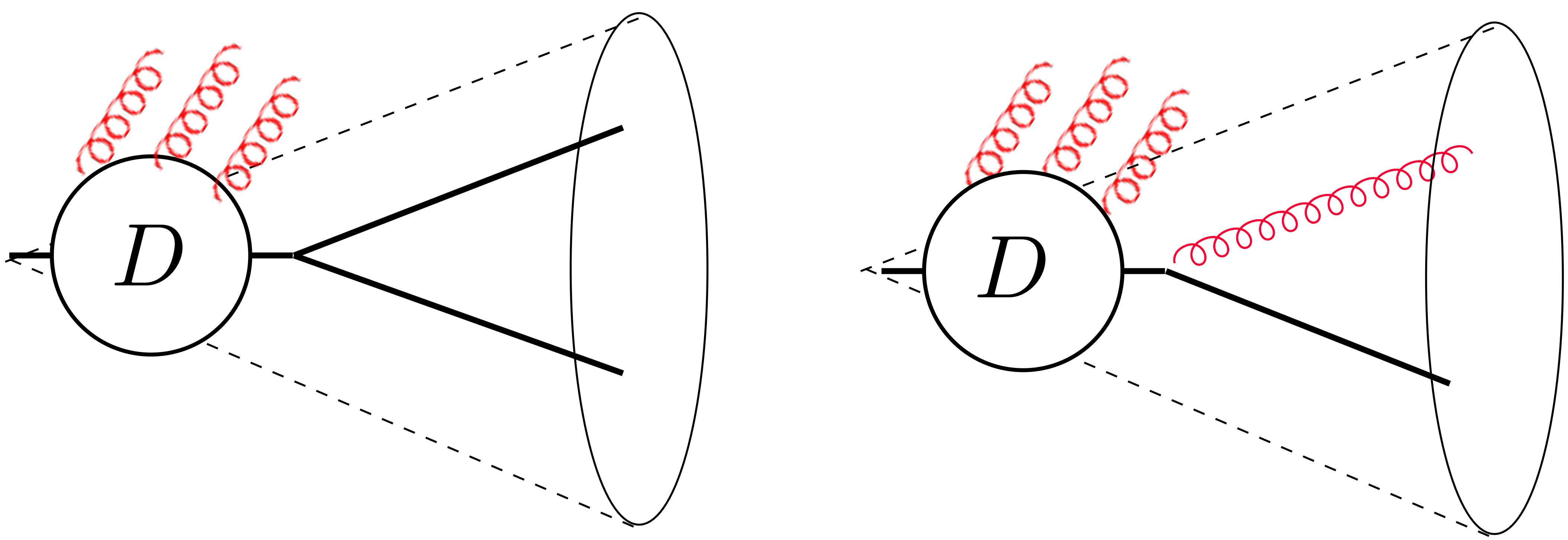
$\Delta(R,\theta)$: Probability not to radiate in [R,θ]

- The z-distribution measures the QCD splitting function

$$p(z_g) \sim P(z_g) \sim 1/z_g$$

How does a 2-pronged structure lose energy?

- In the coherent limit: modification may then come from in-cone:
  1. medium-induced hard gluon radiation
  2. reclustered soft radiation or recoil medium partons (not easily handled analytically)

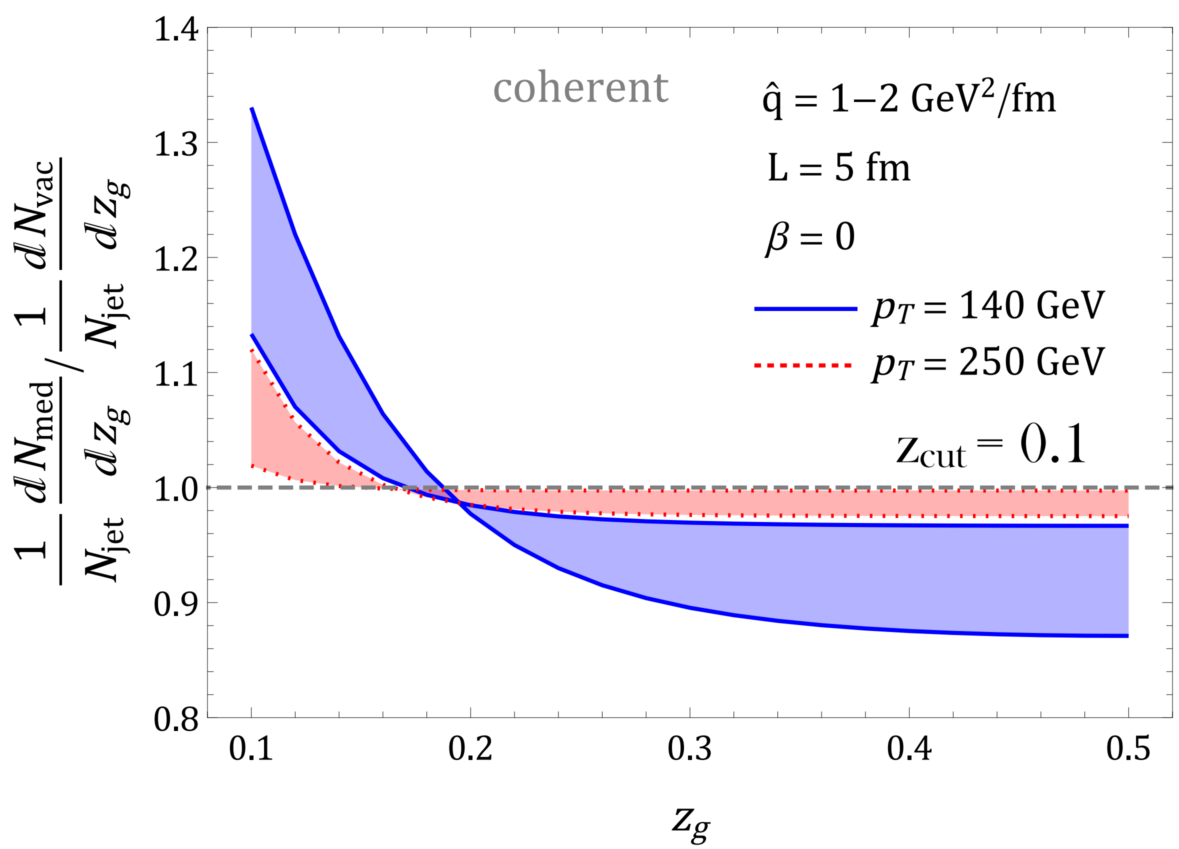


$\Rightarrow$ Expect enhancement of the 2-pronged probability

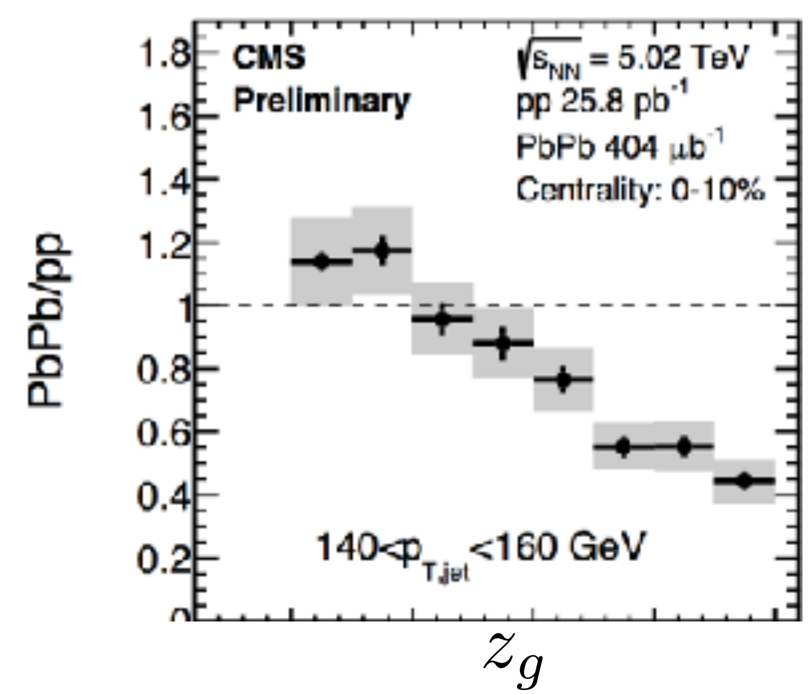
How does a 2-pronged structure lose energy?

- Coherent limit: enhancement of the zg-spectrum at small energies
- Possibility to measure hard medium radiation

MT, Tywoniuk, arXiv:1610.08930



Self-normalized $p(z_g)$ ratio

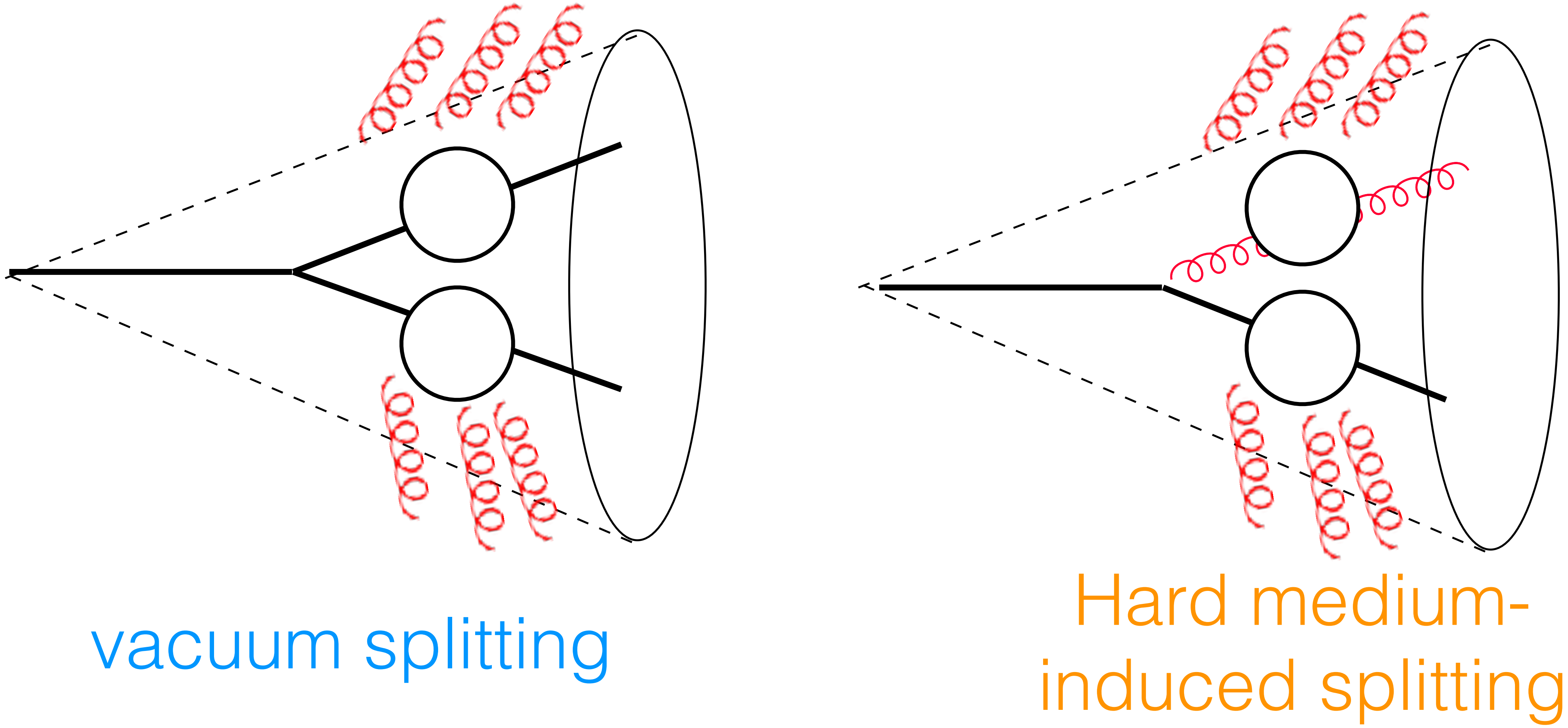


Agrees with data…but what about decoherence?

More information in the yields (2-prong R_{AA})

How does a 2-pronged structure lose energy?

- Incoherent limit: the two subjets lose energy independently
- In this case two pronged structures are expected to be suppressed as compared to proton-proton collisions

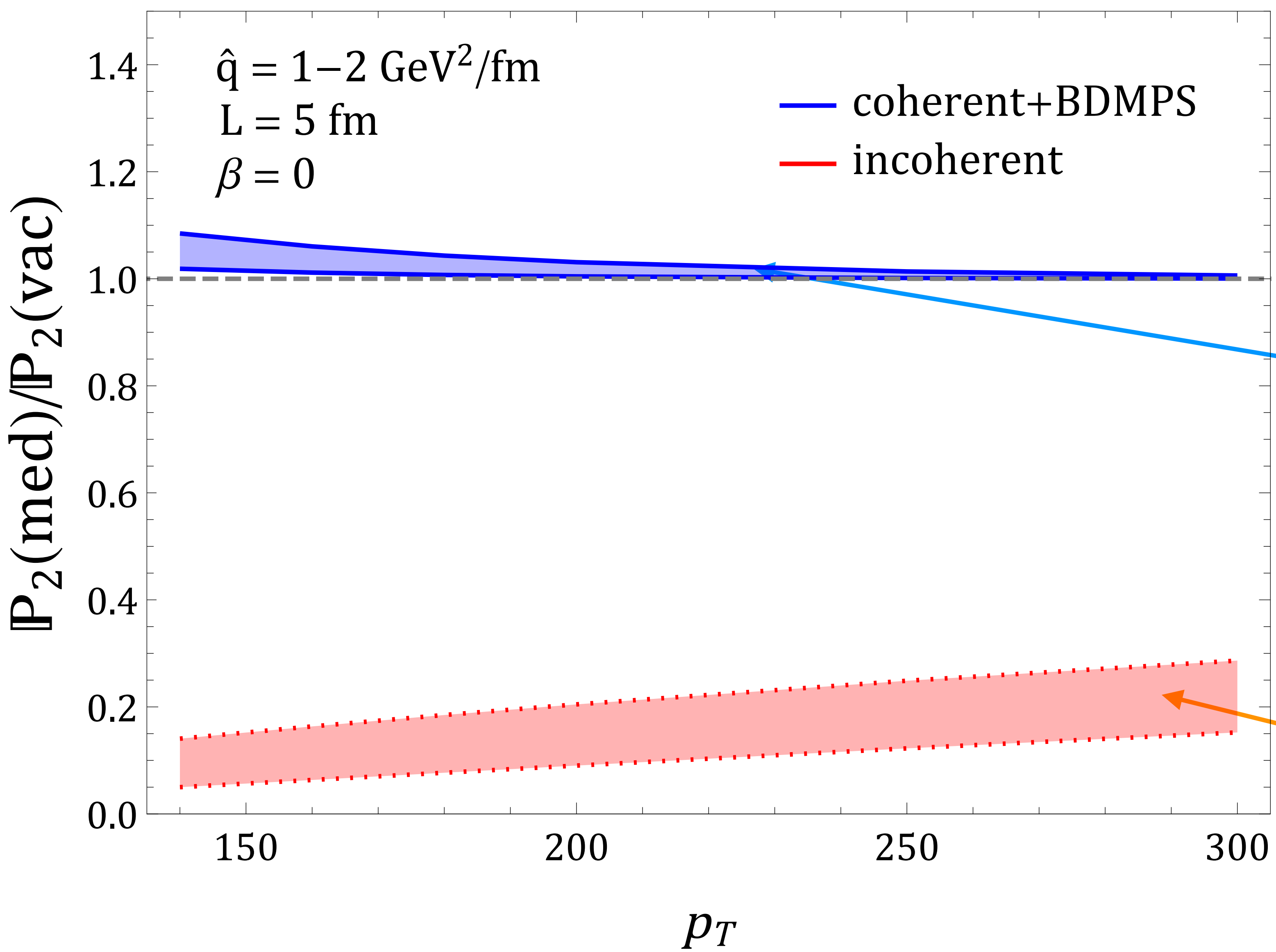


How does a 2-pronged structure lose energy?

- Two-pronged probability

MT, Tywoniuk, arXiv:1610.08930

$$\mathbb{P}_{\text{2-prong}} \equiv \int_{R_0}^{R} \mathrm{d}r_g \int_{z_{\text{cut}}} \mathrm{d}z_g \, p(r_g, z_g)$$



enhancement of 2-prong if coherent energy loss + additional radiation

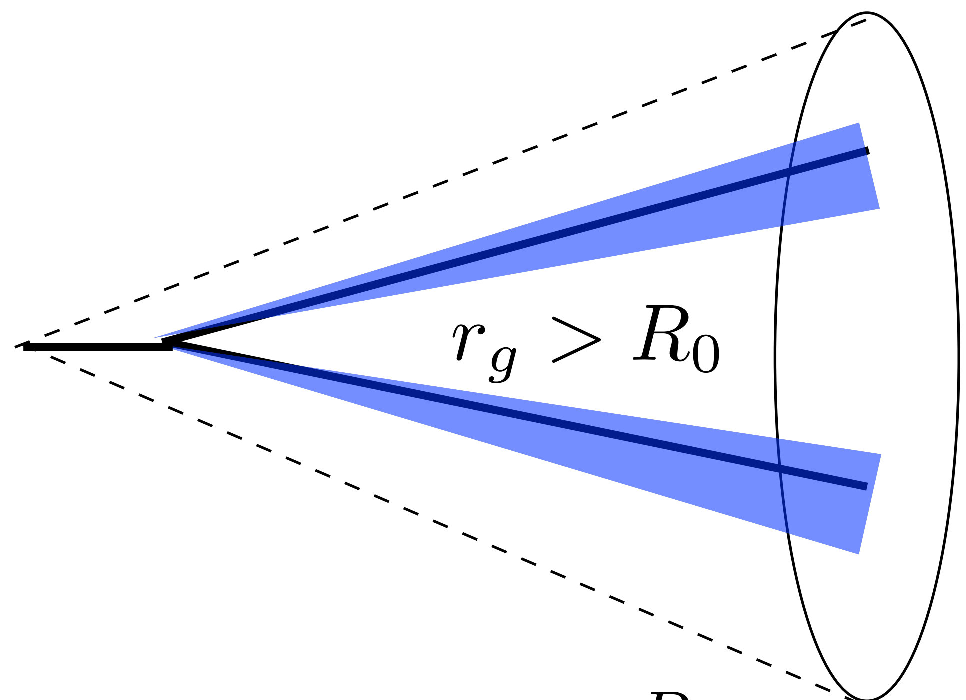
Suppression of 2-prong if incoherent energy loss

Probing decoherence: angular distribution

- Complementary observable to the self-normalized z_g-distribution measured by CMS [CMS-PAS-HIN-16-006]:

angular distribution of 2-pronged substructures

$$R^{\text{2-prong}} \equiv \frac{p_{AA}(r_g)}{p_{pp}(r_g)}$$



- NB: here p(r) is not self normalized!
- Probability conservation:

$$\mathbb{P}_{\text{2-prong}} = \int_{R_0}^{R} \mathrm{d}r_g \, p(r_g)$$

$$\mathbb{P}_{\text{2-prong}} + \mathbb{P}_{\text{1-prong}} = 1$$

[See also N=1 self-normalized dist. Vitev, Chien arXiv:1608.07283]

Probing decoherence: angular distribution

- Interpolation between the coherent and decoherent limits at LO:

$$\frac{\mathrm{d}N_{\text{2-prong}}}{\mathrm{d}p_T^2\mathrm{d}r_g} = (1-\Delta_{\text{med}}(r_g))\,\frac{\mathrm{d}N_{\text{coh}}}{\mathrm{d}p_T^2\mathrm{d}r_g} + \Delta_{\text{med}}(r_g)\,\frac{\mathrm{d}N_{\text{decoh}}}{\mathrm{d}p_T^2\mathrm{d}r_g}$$

- The 2-pronged angular probability distribution:

$$p(r_g) \simeq \frac{\frac{\mathrm{d}N_{\text{2-prong}}}{\mathrm{d}p_T^2\mathrm{d}r_g}}{\frac{\mathrm{d}N}{\mathrm{d}p_T^2}}$$

Inclusive jet spectrum

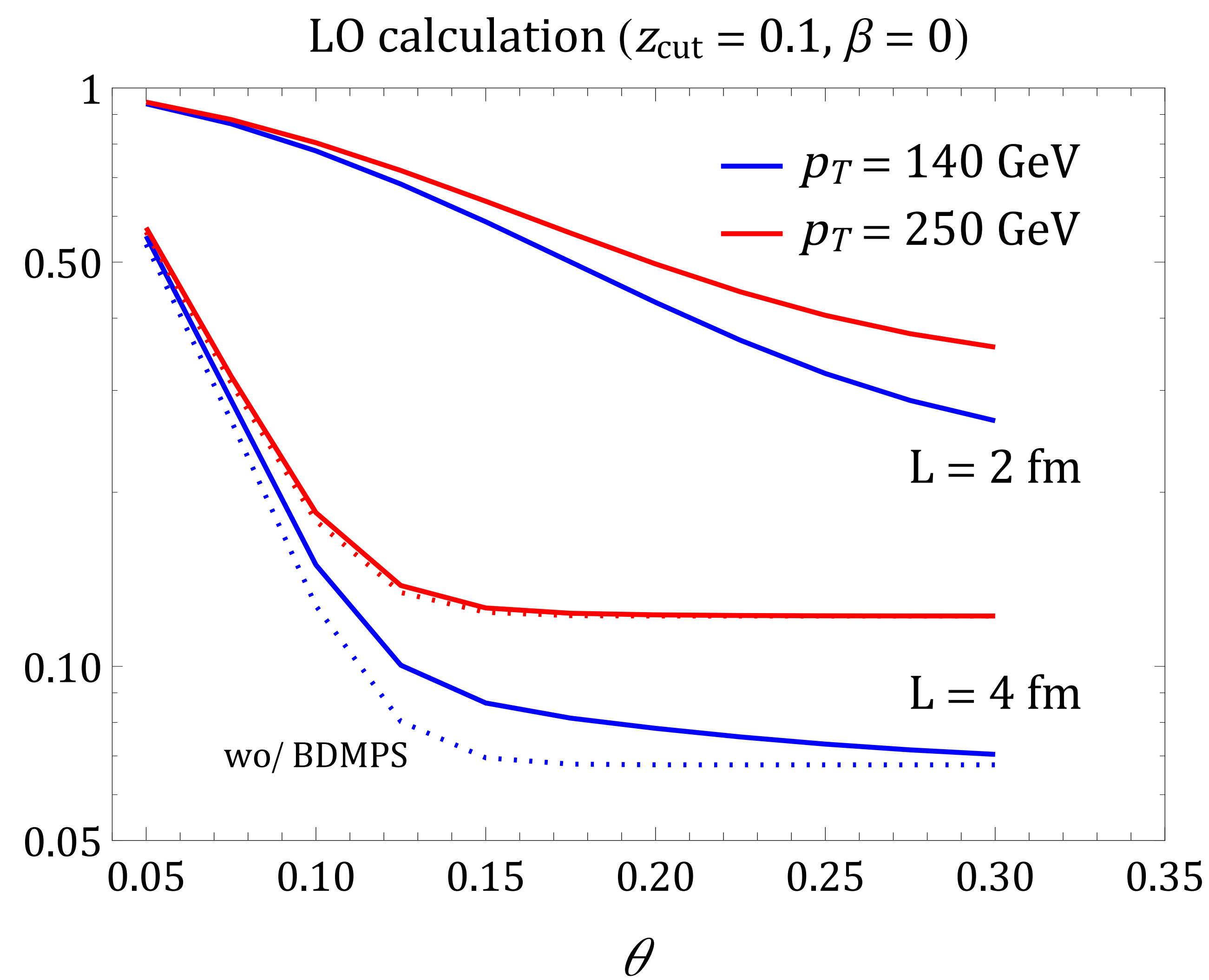
- Again, probability conservation yields

$$\frac{\mathrm{d}N}{\mathrm{d}p_T^2} = \int_{R_0}^{R} \mathrm{d}r_g\,\frac{\mathrm{d}N_{\text{2-prong}}}{\mathrm{d}p_T^2\mathrm{d}r_g} + \frac{\mathrm{d}N_{\text{1-prong}}}{\mathrm{d}p_T^2}$$

Probing decoherence: angular distribution

- Interpolation between the coherent and decoherent limits

$$R^{2\text{-prong}} \equiv \frac{p_{AA}(r_g)}{p_{pp}(r_g)}$$



Strong suppression of 2-pronged probability at large angle (decoherence effects ⇒ jet collimation)

Summary

- Jet substructure studies provide new tools to investigate energy loss mechanisms and color decoherence
- The angular distribution probability of two-pronged structures may provide additional information regarding the transition from the coherence to the decoherence regimes
- *caveat*: sensitivity to background contamination. Investigate jet observables that are less sensitive to possible contamination from soft radiation and recoil partons